RESEARCH STUDIES ON FUSED DEPOSITION ADDITIVE MANUFACTURING 3D PRINTER SYSTEM

A Synopsis submitted

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Doctor of Philosophy

By

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Research Studies on fused deposition additive manufacturing of 3D printer system

Summary:

3D printers are accurate, able to create any intricate object with improved cost and performancecompared to subtractive manufacturing are among the most accessible and versatile machines. Proposed work will be for one of the most useful machines to our community. Most common 3D printer is Fused Deposition Modeling, FDM. There are 3 main families of displacement to navigate the print-head in 3D space, i.e., Cartesian, delta, and polar printer. Significant R&D is required for researching new printer designs in order to obtain high throughput 3D printed parts at low cost and the effect of different process parameters on the part quality of Fused Deposition Modeling (FDM). Essentially, the quality characteristics of FDM build part such as hardness, tensile strength, compressive strength, dimensional accuracy, surface roughness, production time, yield strength and ductility are the primary concerns to the manufacturers and users. In recent years, research has been targeting on identifyingoptimal process parameters, however there are still no perfect optimal parameters for all types of parts and materials. For most parts, there is always a need to adjust parameters to balance a tradeoff between production time, surface finish, and dimensional accuracy. To improve the part quality and mechanical properties for FDM fabricated parts, it is necessary to understand the relationship between material properties and process parameters. Hence, the identification of the critical process parameters and determination of optimum process parameters can lead to the quality improvement of FDM fabricated part. However, the relationships between the process parameters and the part quality and mechanical properties have not been studied enough especially for various types of materials used by the FDM process. Thus, the present research work focuses on the effect of controllable parameters of printer that control the build process, having dominant impact on performance of process, mechanical properties & surface quality of 3D printed job which will be investigated experimentally. This work is important because AM is rapidly gaining popularity as a manufacturing process, further adoption of AM in large-scale manufacturing operations depends largely on enhancements in operation. Research will be aimed to refine, optimize, standardize and indigenised (Bhartiya Swadeshi) FDM based 3D printing technology. Research outcome will certainly provide momentum in making the technology cost-effective so it sustains well, India can too come up with its own range of low cost 3D printers.

Objectives

1. FDM 3D printer experimental test bench facility for conducting experimentation to investigate the effect of controllable parameters of printer will be studied out of this work.
2. FDM machines ranging from desktop models to professional grade systems (available with DEI) will be studied to understand the current technology.
3. Cartesian type 3D printer shall be designed &developed to investigate the effect of controllable parameters of printer.
4. Pilot scale demonstration of low cost Bhartiya Swadeshi 3D printer by optimizing process parameters.
5. To facilitate adoption of 3D printing technologies in domestic manufacturing and to increase manufacturing competitiveness.

Keywords : Additive Manufacturing, 3D Printer, 3D Printing, Fused Deposition Modeling, Process Parameters

Expected Output and Outcome of the research work :

(i) Proposed research investigations will lead to innovation ready for pilot scale demonstration, i.e., translation of research into technology: Bhartiya Swadeshi 3D printer, Indian market will be bestowed with low cost 3D Printing technologies so that India can pace up with the growing trend of 3D Printing

(ii) It is expected that an understanding the effect of process parameters of FDM AM can motivate new 3D printing machine designs that achieve improvements operations .

(iii) Experimental test facility for 3D printers

(iv) Reduction in dependence on International market and make India self-reliant in the additive manufacturing sector

Introduction

Just as nobody could have predicted the impact of the steam engine in 1750 or the printing press in 1450, or the transistor in 1950 - it is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches. 3D printers becoming commercially viable in, but due to their price and complexity, it would be difficult to call any of them accessible or "consumer grade." In India, the work on 3D Printing is in a very nascent stage. It is expected that the 3D Printing market in India will reach over $79 million by 2021.

3D Printers are accurate, able to create almost any intricate object, and can make products out of different types of materials. 3D printing has huge promise for manufacturing parts with improved cost and performance compared to traditional subtractive manufacturing methods. The most commonly used 3D printer is FDM (Fused Deposition Modeling), these printers have different ways to navigate the print-head in 3D space. There are 3 main families of displacement, viz. Cartesian, delta, and polar printer. Polar 3D printers are the simplest printers compared to the other designs as so many components are eliminated as compared to Cartesian printers. This gives a very smooth extrusion, but this technology is essentially experimental at the moment. Therefore to scale-up from prototyping operations and optimization of process (and printed parts) across entails understanding complex and varied interactions between 3D printing machine, production process, process parameters, materials, part design, and part performance. To achieve this, significant R&D is required for researching new printer designs and printing process parameters in order to manufacture high performance 3D printed parts simultaneously at low cost.

Experimental Test facility shall be established out of this proposed work to investigate the effect controllable parameters of printer and of polymers at melted state that control the build process which have dominant impact on performance of process, mechanical properties & surface quality of 3D printed job shall be undertaken by below mentioned experimental work:

1. Cartesian type 3D printer shall be designed & developed to investigate the effect of controllable parameters of printer.

2. Above designed & developed printer shall be analysed on the basis of performance, cost, reliability and maintenance.

3. Processing: effect of extrusion speed, temperature effects (nozzle & print bed), layer thickness, deposition angle, width of the deposited path, spacing between the paths, part orientation, feed rate, flow rate, and viscosity, on the mechanical properties (tensile strength, ductility, etc) and surface roughness of 3D printed parts (comparison among different materials (PLA-ABS) shall also be studied experimentally) shall be studied experimentally on in-house developed printer. Based on different properties and surface roughness values we can decide on the accuracy of 3D printed parts.

4. Part geometry: feature variability and overhangs shall be studied experimentally

5. Material: PLA and ABS in filament form

6. Post-processing: machining of surface roughness to finish near-net parts, heat-treating to improve properties or reduce residual stresses, surface smoothing, cleaning, and sterilization

7. Testing: physical and non-destructive testing (Fractographywill be done on all the tensile tested parts using SEM to discuss the mode of failure of fractured surface of 3d printed parts).

In the proposed research effort will be aimed to refine, optimize and standardize the FDM based 3D printing technology indigenised (Bhartiya Swadeshi). This will make India self-reliant in the field of additive manufacturing. This will mark as a step towards a new era of growth an innovation in India and a new milestone being achieved in the Make in India campaign. Outcome of proposed will certainly provide momentum in making the technology cost-effective so that the technology sustains well in the Indian Market, which will make 3D printing technology an excellent job enabler and promote creation of cottage industries, start-ups, and entrepreneurs in India. Outcome shall be India can too come up with its own range of low cost 3D printing technologies / 3D printers. To achieve this, significant R&D is required for researching new printer designs and printing process parameters in order to manufacture 3D printed parts at fast throughput simultaneously at low cost. Outcome shall be India can too come up with its own range of low cost 3D printing technologies / 3D printers.

Review of status of Research and Development in the subject

International Status:

3D printing is considered as the future of the technology in the world. Most of the world's research is donein universities and most of them are now focusing on these fields to get ahead of each other. 3D printing is amanufacturing phenomenon that will revolutionize factories and mass production in the coming years.ASTM International Committee F42 on AM has organized the span of AM processes into seven categories,differentiated largely by the means of material deposition (ALA17).

Among the variety of advanced manufacturing technologies that are currently emerging, additivemanufacturing stands out as one with enormous potential for changing the distribution of manufacturing andsociety as a whole (HUA13; LIP12). To date, investigations by researchers into the sustainabilityimplications of AM have either been done at a broad level (GEB14; KOH15) or been highly focused on the issue of material and energy consumption (BAU11; FAL15). As a nascent research area in which the impacts of AM on sustainability are unclear. Overall "AM is expected to become a key manufacturing technology in the sustainable society of the future" (HUA13, p. 1201). Many researchers investigated the effect of FDM process parameters on the properties of the final part (ONW14; RAY14) and

available literature discusses improvements to the FDM process such as tool layering path (CHO10) and deposition process analysis (JIN15; WKH15). While other researchers focused on the integration of the AM process into the industrial or the education scheme (LYN16). For materials prone to distortion and warpage, the utilization of the full bed might result with parts of poor quality due to the temperature variations along the edges of the heated bed and different cooling rate, especially in an open FDM system (SUN08). Most FDMprinters have its manufacturer nozzle positioning accuracy procedure. Typical values range between 10 -12.5 microns for the XY plane and 1 - 2.5 microns in the Z direction (ULT17; MAK17). Some equipment has even smaller values (BCN17).

The Additive Manufacturing is a potentially growing market in every manufacturing sector with a globalmarket of $1,843.2 million in 2012 and is expected to grow at a CAGR of 13.5% to reach $3,471.9 million by 2017. The world has sensed the advantages; this technology has to offer.

The potential of 3D printing has been recognized by the US, NAMII (National Additive Manufacturing Innovation Institute) has been set up in the US to provide the innovation infrastructure needed to supportnew additive manufacturing technology and products in order to become a global center of excellence for additive manufacturing. In USA industry is expected to grow at 15.7% annually between 2014 and 2019with an approximated profit of $250.6 million and exports of $599.1 million. The research on 3D printing ranges from strengthening the existing 3D Printing systems and technology to exploring new areas of printing, with new materials, and new methods of manufacturing in layers. ASME, too, has took up AM intothe system for well-structured work documentation and standardization.With reference to Web of Science data (refer following two figures), with a simple subject search on “3Dprinting,” more than 5,000 articles have been indexed in the Core Collection, with the largest concentration of publications appearing in the last three years. It can also be observed that, although 2016 is only abouthalf over, the year’s publications to date on 3D printing have already doubled the 2013 total. In all, thosepublications have been cited thousands of times, with the 2016 year-to-date total of 6,000 citations certain tosurpass 2015’s mark of 8,000 by year’s end. The biggest trend we can expect to continue to grow in 2016 isthe 3D printing.

Today, FDM continues to be a versatile process for rapid manufacturing of extrusion materials in applications including short-run tooling, molds, casting, end-use parts, and more . More than 278,000 desktop 3D printers (under $5,000) were sold worldwide last year, according to Wohlers Associates, publishers of the annual Wohlers Report. According to Wohlers Report 2016, the additive manufacturing (AM) industry grew 25.9% (CAGR – Corporate Annual Growth Rate) to $5.165 billion in 2015. Europe dominates the additive manufacturing for medical devices market since 2012, followed by North America. However, adoption of novel additive manufacturing technologies in the medical field is gaining momentum at a fast pace in emerging nations due to growing educational and awareness efforts of industry players among physicians and patients. Ford is now using carbon3D's clip 3D printers with astonishing results while researching new materials.

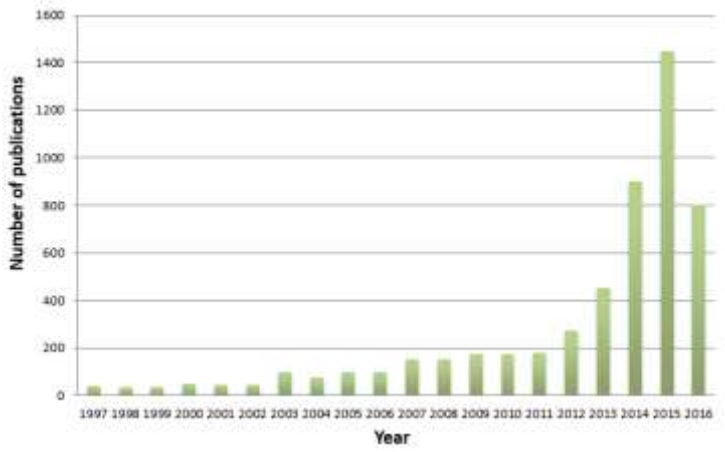

Figure 1: Number of publications each year on 3D printing

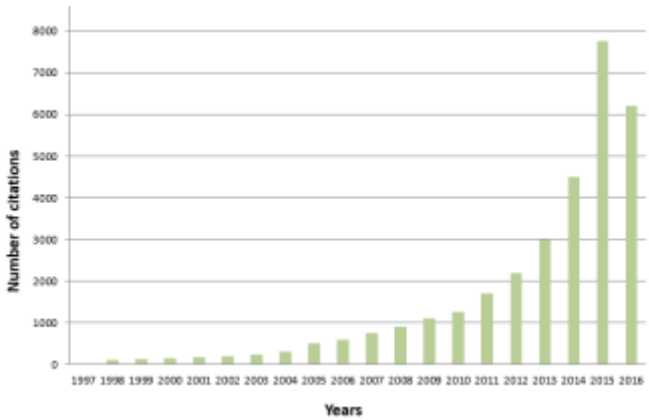

Figure: Number of citations each year on 3D printing

The key players in this market are 3D Systems Corporation (U.S.), 3T RPD (U.K.), ArcamAB (Sweden), Biomedical Modeling, Inc. (U.S.), Envisioned GmbH (Germany), EOS GmbH Electro Optical Systems (Germany), FcubicAB (Sweden), GPI Prototype and Manufacturing Services, Inc. (U.S.), Greatbatch, Inc. (U.S.), LayerwiseNV (Belgium), Lima corporate SPA (Italy), Materializing (Belgium), Medical Modeling, Inc. (U.S.).

A recent patent application by Boeing in support of 3D printing for replacement parts revealed there are currently 20,000 printed parts on board 10 different Boeing fleets *[Boeing (2015) TCT accelerating 3D technologies—Boeing patent. In: TCT magazine + personalize., Available via DIALOG.http://www.tctmagazine.com/3D-printing-news/boeing-files-patent-for-3D-printing-aircraftparts/.]*

In April 2015, "The FAA cleared the first 3D printed part to fly on a commercial jet engine from GE." GE announced that it was working with Boeing to retrofit more than 40 GE90-94B jet engines, which power Boeing's 777 planes, with the 3D printed part—a housing for the T25 sensor. *[GE Reports (2015) The FAA cleared the first 3D printed part to fly in a commercial jet engine from GE. In: GE reports.,http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3D-printed-part-to-fly.]*
47 % of manufacturers surveyed indicate that uncertain quality of the final product was a barrier to the adoption of AM – capture of the complete part pedigree will be critical to product acceptance. *[DARPA (2015) Boosting confidence in new manufacturing technologies., Defense Advanced Research Projects Agency (DARPA). http://www.darpa.mil/news-events/2015-05-29.]*

National Status:

When we look at the 3D printing market across the globe, India features in the top 10 countrieswith 7 manufacturers. US, China, and Germany top the list with 66, 42, and 22 manufacturers, respectively. The adoption of 3D printing in India is still at an early stage when compared to other parts of the world; but manufacturers across verticals are seeing the benefits of 3D printing and the value it brings. Currently, India primarily imports 3D printers from China, US, and Germany, but various government initiatives aiming to

boost domestic manufacturing will result in more local3D printing devices. With growing focus on Make in India, lot of Indian manufacturers placing emphasis on producing goods locally, therefore, manufacturers would need a technology which is both cost and time effective. According to the 6WResearch report, the total Indian market for 3D printing will be around $79million by 2021, states that fused deposition modeling (FDM) based 3D printers dominate theIndian market.

NitiAyog, Government of India has put 3D Printing / Additive Manufacturing as one of the 15disruptive technologies in science and technology roadmap for India. They have installed 3Dprinters in 500 schools in first phase across the country and planning to take this drive to 2000schools.

"3D printing will take off in India as multinational vendors offer their 3D printers locally and indigenous startups come to market with not only consumer but also enterprise-class 3D printers," said Pete Basiliere, vice president at Gartner.

Prof. Balkrishna C Rao, IIT-M has emphasised 3D printing as potential areas for sustainable manufacturing and urged the Indian academia and industry could also focus on some of the latest disruptive technologies. [Need for Sustainability and Innovations in Indian Manufacturing, Yojna, Vol. 59, April 2015]

In 2015, Hindustan Aeronautics (HAL), sole manufacturer of military aircraft in India, used 3D printing technology to manufacture components for its Rs. 458-crore 25-kN aircraft engine project. Dr. U. Chandrasekhar, Former Scientist GTRE-DRDO, has pioneered the use of 3D printing in Defence R&D and setup the first ever Additive Manufacturing centre at Gas Turbine Research Establishment (GTRE). GTRE has employed 3D printing to print ABS Plastic Quality

Kaveri engine components for a detailed study. In his words: "FDM Cuts Time to Prototype Jet Engine from 1 Year to 6 Weeks. With FDM we created an engineering prototype that perfectly reflected our design intent and facilitated the complex engine development". Since 2002, Prof. K. P. Karunakaran IITB is leading the country at fore front of 3D printing / additive manufacturing. He has established a dedicated state of the art Rapid Prototyping Centre at IITB. Prof. J. RamKumar, IITK, Prof. PVM Rao, IIT-D, Prof. C S Kumar, IIT-

KGP, Prof. P M Pandey, IIT-D, Prof. BB Ahuja, COE Pune, have established 3D printing centres at respective IITs and has taken number of initiatives aimed at deeply promoting and supporting progress of 3D printing research and development in country. Prof. B. Ravi, IIT-B is pioneering work in rapid tooling and rapid prototyping. Prof. S SPande, IIT-B is developing optimal strategies for AM, Prof. BikramjitBasu, IISc working on 3D printing of porous scaffolds. All these professors are responsible for anumber of initiatives aimed at promoting and supporting 3D printing research and development in India.

Central Manufacturing Technology Institute (CMTI), Bangalore has established facilities for Rapid Product Development (RPD) currently headed by Dr. C.K Srinivasa. It offers total solution for rapid product development and consultancy. College of Engineering, Pune (COEP) in association with Central Manufacturing Technology Institute (CMTI), Bangalore are launching a one year post graduate diploma course in "Additive Manufacturing". CMTI has also started M.Tech programme in Additive Manufacturing at NIT Warangal.

In India, work on 3D Printing is mostly limited in the study or application end of the technology. Others are engaged in the testing with material deposition planning. In the corporate world, there are many companies that provide prototyping solutions using variety of 3D Printer. Wipro Infrastructure Engineering where a combination of additive & subtractive technologies are used to produce functional components that use innovative designs. But due to the high cost of industrial grade 3D Printers, there are only a few corporate that dominates the market. Being more or less successful in experimenting with this technology, it seems that enterprises now understand the hidden potential of 3D printing.

The research in India tangents to just the study of the process and its application. Had these printers have been available at affordable prices, more and more prototyping centre would have sprung up in the market, breaking the monopoly of a few. Not much is aligned to the development of new processes and with new materials, while making the process and technology affordable and suitable in the Indian market so that India could make the best use of this technology.

Importance of the proposed work in the context of current status

The 3D printing industry has tremendous potential to revolutionize the market in India, with a possibility of creating several jobs for part-suppliers and other ancillaries in addition to the assembly companies. The current availability of 3D printers in India is through a handful of companies like Makerbot and Stratasys, which are too expensive to purchase. So, there is a need to make indigenous 3D printers with high speed printing, best quality and yet lower cost.Significant R&D is required for researching new printer designs in order to obtain high throughput 3D printed parts at low cost. Therefore, it is of interest to understand the varied interactions between machine, process parameters, material, part design, and part performance. The cost that we are targeting is not just physical cost but also the human resource cost, maintenance cost, operational cost etc.

This work is important because AM is rapidly gaining popularity as a manufacturing process due in part to its ability to create unique geometries with unique materialcompositions across an unprecedented range of length scales from single microns to multiple meters. Further adoption of AM in large-scale manufacturing operations hinges largely on improvements in throughput and so it is vital to understand the performance limits of current AM methods in order to invent new machine and process designs. Since its conception, FDM technology has evolved in terms of scale and material capability. Despite this evolution in capability, the fundamental mechanisms used in FDM technology have evolved very little from their original designs. Filament material is still fed into a conduction liquefier using a pinch wheel extruder. The nozzle and build platform are still positioned using a series gantry system driven bystepping-motors. As a result, FDM print rate has not improved. The high throughput FDM approach has promising future applications to the extrusion AM of nanocomposite polymer resins, highthroughput AM of high performance thermoplastics, and adaptation to large-scale extrusion AM systems. Eventually, this area of research should result in a robust set of rules that can fundamentally reduce the costs associated with FDM and can assist its ascent as a feasible full-scale manufacturing process.

The work is aimed to provide a cost-effective solution to 3D Printing and provide an alternative to the foreign 3D printers that have a high cost attributed to them. Moreover, while the research carried out world-

wide is to make technology for the industries, none is aiming to make the technology for the masses and small entrepreneurs who can earn quite well using this technology. The proposed work paves a way to bring out this technology in the reach of everyone by making it affordable and thus suitable to the India Market. This will also enable many self-employment opportunities and make people mint money using the technology. This will prove to be a next revolution in the manufacturing industries with immense scope for technological and economic advancement. Establishment of Experimental Test facility out of this proposed work to investigate the effect of below mentioned controllable parameters will novel and first of its kind in Country and the printers will be designed to provide the best user experience enabling any non-technical person to easily operate the machine. The various sub-systems will be optimized to get best print results. Exhaustive experimental study shall be accomplished out of this proposed work.

Methodology

Material extrusion is based on molten material, which is extruded through a printing head. Themost popular and used material extrusion technology is fused deposition modeling. FDMtechnology consists of equipment, which feeds a plastic filament wire into a liquefier chamber. The chamber is heated into a temperature suitable for melting desired plastic material according toits melting point. The filament softens and melts inside the liquefier and the filament pulling rolls pushes the molten plastic through the nozzle along with the non-molten filament. The energyrequired in the melting process is produced by a heater connected along with a theremistor to thenozzle. The temperature should be as low as possible in the melting point area to avoid materialdegradation inside the chamber or even burning which could leave burn residues inside thechamber. The molten filament is deposited onto the platform or already extruded surface by layerswhere it cools into room temperature and bonding with the base material. The height of theextruded layer depends on the G-code generated by the slicing software while the width of thelayer depends on the diameter of the extrusion nozzle. The extrusion process starts fromunwinding the plastic filament material from a roll. The feeding of the wire is handled with pinchroller system, which is located in the extrusion head. Movement of the extrusion head depends of the printer type. The filament feeding equipment feeds the filament to the printing head, which contain the liquefier for melting the plastic. The head includes also a cooler, which regulates the temperature of the printing head. The extrusion head contains an input for the

filament and sinks for dissipating excess heat. The heating unit melts the plastic and the extrusion is done through the nozzle. As the material solidifies after extrusion, the shrinkage caused by cooling can be minimized by using a chamber, which is heated. The platform where the material is extruded is a XY-plane table and is usually moved by roller screw system. The popularity of the technology can be seen nowadays as a variety of different printers. Printers are built in very compact shape and easy to use even for a household use and the prices are starting to be in a reasonable level.

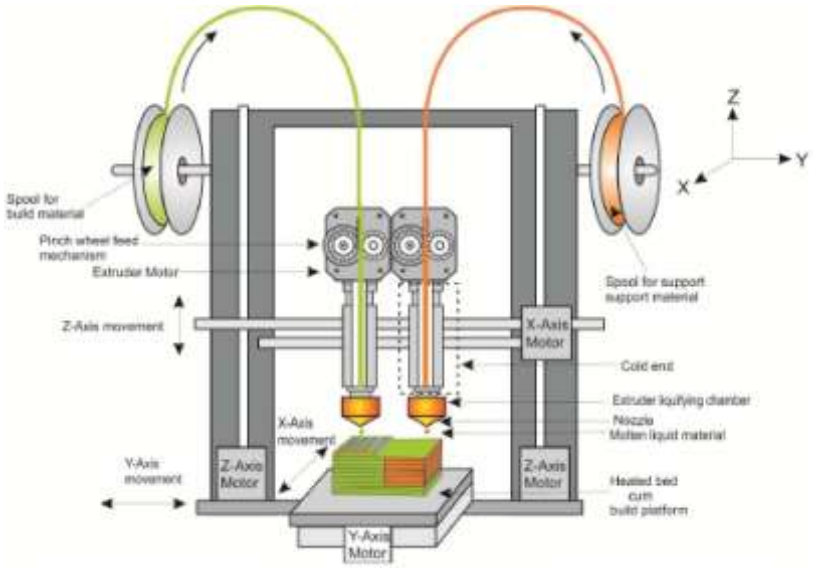

Figure: Complete FDM AM process machine setup

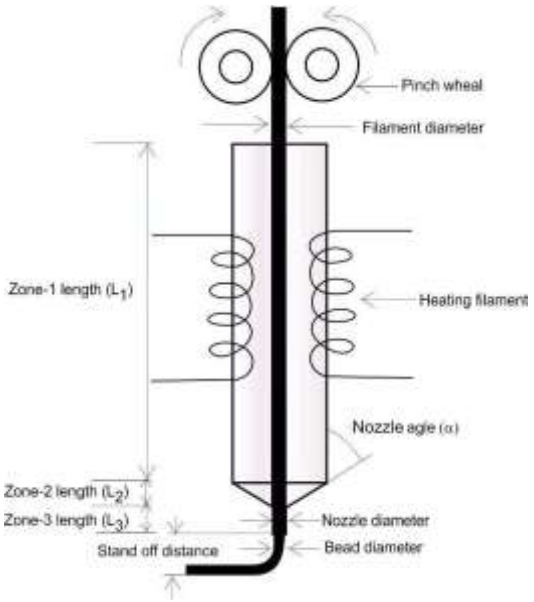

Figure : Various Zones in extruder nozzle

1. Thorough literature survey of the latest advancements in the 3D printing technology.
2. Development of experimental test bench for the range of 3D Printers.

3. Thorough study of the various elements of the 3D Printer:
    - Electronics
        - the microcontroller board
        - the stepper motor and its drivers
        - heat bed
        - hot end
    - Mechanical
        - Frame and support materials (mild steel, acrylic, aluminum etc.)
        - End-effector traversing mechanism.
    - Process
        - Optimal heat bed and hot-end temperature for various plastic that can be used in FDM based 3D Printers.
        - The viscosity of the material required when fed to the 3D printer for viscous material.
4. Print optimization by tweaking the various slicing options.
5. Experimenting with various hot-end.
6. Experimenting with printing in different settings.
7. Designing the printer as light and compact as possible so as to make it viable for desktop 3D Printing.

1. Cartesian type 3D printer shall be designed & developed to investigate the effect of controllable parameters of printer.

2. Above designed & developed printer shall be analysed on the basis of performance, cost, reliability and maintenance.

3. Processing: effect of extrusion speed, temperature effects (nozzle & print bed), layer thickness, deposition angle, width of the deposited path, spacing between the paths, part orientation, feed rate, flow rate, and viscosity, on the mechanical properties and surface roughness of 3D printed parts (comparison among different materials (PLA-ABS) shall also be studied experimentally) shall be studied experimentally on in-house developed printer.

4. Part geometry: feature variability and overhangs shall be studied experimentally

5. Material: PLA and ABS in filament form

6. Post-processing: machining of surface roughness to finish near-net parts, heat-treating to improve properties or reduce residual stresses, surface smoothing, cleaning, and sterilization

7. Testing: physical and non-destructive testing (Fractography).

In the proposed research effort will be aimed to refine, optimize and standardize the FDM based 3D printing technology indigenised (Bhartiya Swadeshi).

As mentioned earlier mechanical properties of 3D printed samples are effected by, such as layer thickness, raster angle, build orientations, fill pattern, air gap and model build temperature. Layer thickness is the thickness of the layer deposited by the nozzle. Raster angle is the direction of raster with respect to the loading direction of stress, as shown in Figure. Air gap is the distance between two adjacent deposited filaments in the same layer. The number of contours is the number of filaments initially deposited along the outer edge. Bead width is the width of the filament deposited by the 3D printer nozzle. Experiments will be performed with an extruder coupled with temperature and pressure sensors to simulate the FDM process. For testing samples will be fabricated in five different layer orientations.

Studying the influence of layer thickness and raster angle on the mechanical properties of 3D-printed parts. Samples with three different layer thicknesses (200, 300 and 400μm) and raster angles (0^0, 30^0, and 45^0) shall be studied. Tensile, compressive and bending strengths will be tested. The optimal mechanical properties of various samples will be found at a particular layer thickness.

Comprehensive research on the various 3D printing parameters will be conducted and the printers will be designed to provide the best user experience enabling any non-technical person to easily operate the machine.

The various processes will be optimized to get best print results. The post processing methods will be tested to get best print results.

Subsequently, with the low cost 3D printer available out in the market, which could manufacture parts well, a wave of demand of 3D printers will flow and then the country will be able to make the best use of the technology which is currently not possible due to the high price attributed to these printers.

References

GE Additive Manufacturing http://www.ge.com/stories/additive-manufacturing

Pratt &WhitneyAdditiveManufacturingInnovationCenter

http://today.uconn.edu/blog/2013/04/pratt-whitney-additive-manufacturing-innovationcenter-opens-at-uconn/

Fraunhofer Additive Manufacturing Alliance http://www.fraunhofer.de/en/institutesresearch-establishments/groups-alliances/additive-manufacturing-alliance.html

[ALH15] Alhart T, "GE's digital marketplace to revolutionize manufacturing", In: GE Global Research., Available via DIALOG. *http://www.geglobalresearch.com/news/press-releases/ges-digital-marketplace-to-revolutionize-manufacturing*, 2015.

[AME14] America Makes, "Fundamentals of Additive Manufacturing Materials & Processes", [Online]. Available: *https://americamakes.us/news-events/events/event/12-fundamentals-of-additive-manufacturing-materials-processes*, 2014.

[Amr16] Amar Phatak, Pande S.S, "Optimum Strategies for hollowing and part orientation in additive manufacturing", International Journal of Precision Technology, v6, Issue 1, pp 61-77, 2016.

[AST13] ASTM F2792-12a: "Standard Terminology for Additive Manufacturing Technologies", ASTM International, West Conshohocken, 2013.

[Bap05] Vijay P. Bapat and K.P. Karunakaran, "Rapid Prototyping: The Dawn of Slice Age", Search, Vol 8 No. 1 pp. 341-350 [*PDF*], January 2005.

[BAS14] Pete Basiliere, "How 3-D Printing Disrupts Business and Creates New Opportunities", Gartner G00249922, April 2014.

[BIC10] BICKEL, B., BÄCHER, M., OTADUY, M. A., LEE, H. R., PFISTER,H., GROSS, M., AND MATUSIK, W., "Design and fabrication of materials with desired deformation behavior", ACM Trans. Graph. 29, 4 (July), 63:1–63:10, 2010.

[BIE14] John Biers, "3D Printing Could Become A $13 Billion Industry", Business Insider, November 09, 2014, accessed at *http://www.businessinsider.com/afp-from-earphones-to-jet-engines-3d-printing-takes-off-2014-11#ixzz3M EvO37Uy*, 2014.

[BIG14] J. Biggs, "MIT Students Create An Ice Cream Printer", Available: *http://techcrunch.com/2014/07/16/mit-students-create-an-ice-cream-printer*, 2014.

[BRA10] Brajlih, T., Valentan, B., Balic, J., &Drstvensek, I., "Speed and accuracy evaluation of additive manufacturing machines", Rapid Prototyping Journal, 17(1), 64-75, 2010.

[BUL15] G. Bull, H. Haj-Hariri, R. Atkins, and P. Moran, "An Educational Framework for Digital Manufacturing in Schools", 3D Print. Addit. Manuf., vol. 2, no. 2, pp. 42–49, 2015.

[CAM13] CAMPBELL, T. A., AND IVANOVA, O. S., "3D printing of multifunctional nanocomposites", Nano Today 8, 2, 119 – 120, 2013.

[CAN14] Canalys, "3D printing market to grow to US$16.2 billion in 2018," news release, March 31, *http://www.canalys.com/newsroom/3d-printing-market-grow-us162-billion-2018#sthash.jovzItNE.dpuf*, 2014.

[CHA11] Chang, S., & Huang, B., "Studies on profile error and extruding aperture for the RP parts using the fused deposition modeling process", International Journal of Advanced Manufacturing Technology. 53, 1027-1037, 2011.

[CHE13] CHEN, D., LEVIN, D.I. W., DIDYK, P., SITTHI-AMORN, P., AND MATUSIK, W., "Spec2Fab: A reducer-tuner model for translating specifications to 3D prints", ACM Trans. Graph. 32, 4, 135:1–135:10, 2013.

[DEL15] DeloitteUniversity, "3D opportunity: The course on additive manufacturing for business leaders", [Online]. Available: *http://www2.deloitte.com/global/en/pages/about-deloitte/articles/3D-printing-mooc.html*, 2015.

[DIM13] DIMAS, L. S., BRATZEL, G. H., EYLON, I., AND BUEHLER, M. J., "Tough composites inspired by mineralized natural materials: Computation, 3D printing, and testing.", Advanced Functional Materials 23, 36, 4629–4638, 2013.

[ECO12] "Print me a phone," *The Economist* (US), July 28, *http://www.economist.com/node/21559593*, 2012.

[FOR15] Formlabs, "Form 1 + High-Resolution Desktop 3D Printer", [Online]. Available: *http://formlabs.com/products/form-1-plus/*, 2015.

[GAL09] Galantucci, L.M., Lavecchia, F., Percoco, G., "Experimental study aiming to enhance the surface finish of fused deposition modeled parts", CIRP Annals - Manufacturing Technology, 49(2), pp. 189-192, 2009.

[Gog08] Gogate A.S, Pande S.S, "Intelligent layout planning for rapid prototyping", International Journal of Production Research, v46, Issue 20, pp 5607-5631, 2008.

[GRA15] Granta, "Granta Design announces new solution for Additive Manufacturing data", Granta Material Intelligence. *https://www.grantadesign.com/news/2015/Additive.shtml*, 2015.

[HEA14] Brian Heater, "The CubeJet promises pro-level 3D printing in a consumer form factor for under $5,000", Engadget, January 7, *http://www.engadget.com/2014/01/07/cubejet/*, 2014.

[HOR14] Horvath, J., "Mastering 3D printing". New York, NY: Springer Science + Business Media, LLC, 2014,

[Kar00] K.P. Karunakaran, P. Vivekananda Shanmuganathan, Sanjay Janardhan Jadhav, Prashant Bhadauria and Ashish Pandey, "Rapid Prototyping of Metallic Parts and Moulds", Journal of Materials Processing Technology, Vol. 105, pp. 371-381, 2000.

[Kar04] K.P. Karunakaran, SreenathbabuAkula and Vishal Pushpa, "Hybrid Layered Manufacturing: Direct Rapid Metal Tool-Making Process", I MECH E Journal of Engineering Manufacture, Vol. 218, No. B12, pp. 1657-1665, December 2004.

[KAT13] Katt RJ, "Materials manufacturing capabilities for sustaining defense systems", National Academy of Sciences Press, Washington DC, ISBN: 978-0-309-26757-1, 2013.

[Kel11] "3D Printing: The New Industrial Revolution", KelleySchool of Business – IndianaUniversity, 2011.

[KEL14] Kelly, "Additive Manufacturing at EWI.", EWI. *https://ewi.org/eto/wp-content/uploads/2015/amcEWI716/00_Kelly.pdf*, 2014.

[KEL15] Kellner T, "Personalized production: the Brilliant Factory will match the right parts with the right tools", In: GE Reports., Available via DIALOG. *http://www.gereports.com/post/114774680705/personalized-production-the-brilliant-factory/*, 2015.

[Kum16] Alok Kumar, Sourav Mandal, SrimantaBarui, Ramakrishna Vasireddi, Uwe Gbureck, Michael Gelinsky, BikramjitBasu,

"Low temperature additive manufacturing of three dimensional scaffolds for bone-tissue engineering applications", Materials Science and Engineering, R: ReportsVolume 103, Pages 1–39, May 2016

[MAS04] Massod S H, Song W Q, "Development of new metal/polymer for rapid tooling using FDM", Materials & Design Vol 25, No 7, p.587-594. ISSN 0261-3069, 2004.

[MAT14] Materials Today, "US$450,000 grant to develop better 3D printing simulation", In: Materials today. *http://www.materialstoday.com/additive-manufacturing/news/us450000-grant-to-develop-better-3d-printing/*, 2014.

[MIT15] MIT Professional Education, "Additive Manufacturing: From 3D Printing to the Factory Floor," Available: *http://web.mit.edu/professional/short-programs/courses/additive_manufacturing.html*, 2015.

[Mye15] "The Impact of 3D Printing on the World Container Transport", M. Ye, DelftUniversity of Technology, 2015.

[NAM15] "NAMII." [Online]. Available: *http://www.manufacturing.gov/nnmi_pilot_institute.html*.

[NIS14] "Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion", National Institute of Standards & Technology (NIST Special Publication 1176), *http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf*, December 2014.

[NOT15] The University of Nottingham, "EPSRC Centre for Doctoral Training in Additive Manufacturing," Available: *http://www.nottingham.ac.uk/additivemanufacturing/index.aspx*, 2015.

[NTU15] "NTU launches $30 million 3D printing research centre." Available: http://media.ntu.edu.sg/NewsReleases/Pages/newsdetail.aspx?news=1b6303cf-3063-4bd1-b8ec-d738c7457a3f.

[OAK14] Oak Ridge National Laboratory, "ORNL, CINCINNATI partner to develop commercial large-scale additive manufacturing system," news release, February 17, *http://www.ornl.gov/ornl/news/news-releases/2014/ornl-cincinnati-partner-to-develop-commercial-large-scale-additive-manufacturing-system--.*, 2014

[OXM11] OXMAN, N., "Variable property rapid prototyping", Journal of Virtual and Physical Prototyping (VPP) 6, 1, 3–31., 2011.

[PAN03] Pandey, P. M.; Reddy, N. V.; Dhande, S. G., "Real time adaptive slicing for fused deposition modeling", International Journal of Machine Tools and Manufacture, 43, 1 pp. 61–71, 2003.

[PEI11] E. Pei, R. I. Campbell, and D. Beer, "Entry-level RP machines: how well can they cope with geometric complexity?," Assembly Automation, vol. 31, no. 2, pp. 153-160, 2011.

[PEN14] Peng, A., Xiao, X., & Yue, R., "Process parameter optimization for fused deposition modeling using response surface methodology combined with fuzzy inference system", International Journal of Advanced Manufacturing Technology, 73, 87-100, 2014.

[POP15] Popular Mechanics, "MIT Creates a 3D Printer for Glass", Available: *http://www.popularmechanics.com/technology/a17012/mit-creates-a-3D-printer-for-glass/*, 2015.

[PWC14] PWC, "3D printing and the new shape of industrial manufacturing.", PWC. June 2014., p 19, Available via DIALOG. *http://www.pwc.com/us/en/industrial-products/assets/3d-printing-next_manufacturing-pwc.pdf*, 2014.

[RAY14] Rayegani, F., &Onwubolu, G. C.: "Fused deposition modelling (FDM) process parameter prediction and optimization

using group method for data handling (GMDH) and differential evolution (DE)", The International Journal of Advanced manufacturing Technology, 2014.

[ROB13] Roberson, D.A., Espalin, D., & Wicker, R.B., "3D printer selection: A decision-making evaluation and ranking model", Virtual and Physical Prototyping, 8(3), 201-212, 2013.

[SIM10] T. Simonite, “I, Replicator: Self-replicating machines come of age", New Scientist, vol. 206, no. 2762, pp. 40-43, 29-May-2010.

[SIN13] Singh, R., "Process capability analysis of fused deposition modeling for plastic components", Rapid Prototyping Journal, 20(1), 69-76, 2013.

[SMR13] “Innovation Lessons from 3D Printing”, Sloan Management Review, Winter 2013.

[SOO09] Sood, A. K., Ohdar, R. K., Mahapatra, S. S.: "Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method", Materials & Design, 30(10, pp.4243–4252), 2009.

[STU14] Stucker B, "Advanced modeling for Additive Manufacturing", s.l.: 3DSIM, LLC (copyright)., pp 1–24, Available via DIALOG. *https://fabricationmecanique.files.wordpress.com/2014/11/3dsim-information.pdf*, 2014.

[TEX15] “The W . M . Keck center for 3d innovation”, University of Texas El Paso, El Paso, TX, 2015.

[THR04] Thrimurthulu, K.; Pandey, P. M.; Venkata Reddy, N., "Optimum part deposition orientation in fused deposition modeling", International Journal of Machine Tools & Manufacture, 44, 6(2004), pp. 585-594.

[Vas15] Ramakrishna Vasireddi , BikramjitBasu , "Conceptual design of three-dimensional scaffolds of powder-based materials for bone tissue engineering applications", Rapid Prototyping Journal, Vol. 21 Iss: 6, pp.716 – 724, 2015.

[VID13] VIDIM˙C E, K., WANG, S.-P., RAGAN-KELLEY, J. AND MATUSIK, W., "OpenFab: A programmable pipeline for multi-material fabrication", ACM Trans. Graph. 32, 4 (July), 2013.

[WOH14] T. Wohlers, “Tracking Global Growth in Industrial-Scale Additive Manufacturing”, Mary Ann Liebert, Inc. 140 Huguenot Street, 3rd Floor New Rochelle, NY 10801 USA, Mar. 2014.

[WOH15] T. T. Wohlers and T. Caffrey, Wohlers "Report 2015: 3D Printing and AdditiveManufacturingState of the Industry Annual Worldwide Progress Report", Fort Collins, CO: Wohlers Associates, 2015.

[WOH16] T. T. Wohlers and T. Caffrey, Wohlers "Report 2016: 3D Printing and AdditiveManufacturingState of the Industry Annual Worldwide Progress Report", Fort Collins, CO: Wohlers Associates, 2016.

[ZHA08] Zhang, Y., & Chou, K., "A parametric study of part distortions in fused deposition modeling using three-dimensional finite element analysis", Journal of Engineering Manufacture. 222, Part B, 2008.

[ZHO13] ZHOU, C., CHEN, Y., YANG, Z., AND KHOSHNEVIS, B., "Digital material fabrication using mask-image-projection based stereolithography", Rapid Prototyping Journal 19, 3, 153–165, 2013.